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Short communication

Modelling creep behaviour of the human intervertebral disc

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ABSTRACT

The mechanical behaviour of an intervertebral disc is time dependent. In literature different constitutive equations have been used to describe creep. It is unsure whether these different approaches yield valid predictions. In this study, we compared the validity of different equations for the prediction of creep behaviour. To this end, human thoracic discs were preloaded at 0.1 MPa for 12 h, compressed (0.8 MPa) for 24 h and finally unloaded (0.1 MPa) for 24 h. A Kohlrausch-Williams-Watts (KWW) model and a Double-Voight (DV) model were fitted to the creep data. Model parameters were calculated for test durations of 4, 8, 12, 16, 20 and 24 h. Both models described the measured data well, but parameters were highly sensitive to test duration. The estimated time constant varied with test duration from 3.6 to 17 h. When extrapolating beyond test duration, the DV model under-estimated and the KWW model over-estimated creep. The 24 h experiment was still too short for an accurate determination of the parameters. Therefore, parameters obtained in this paper can be used to describe normal behaviour, but are not suitable for extrapolation beyond the test duration.

1. Introduction

Mechanical loading on the spine is mainly axial loading, caused by gravity and muscle forces. The diurnal loading pattern in humans typically consists of 16 h loading and 8 h of relative rest (van der Veen et al., 2005; O'Connell et al., 2011b). This loading pattern leads to an overall decrease of disc height during daytime and an increase during the night. In-vitro measurements showed asymmetrical mechanical behaviour of the disc with respect to loading and unloading. A long recovery time was required to compensate the effect of the loading phase (van der Veen et al., 2005, 2007).

The deformation of the intervertebral disc is non-linear and time dependent. It is typically a decay function in which two regimes are superimposed. During the first regime the deformation rate is high, during the second regime the deformation rate progressively slows down (Johannessen et al., 2004; van der Veen et al., 2005). The time constant of the long-term behaviour is the time constant of the second regime. In recent literature, various models have been used to describe and predict deformation of the disc over time: e.g. a stretched exponential function model (KWW) (Johannessen et al., 2004) and a Double-Voight model (DV) (O' Connell et al., 2011a). The time constant of the slow regime varies from minutes in small animals to hours in humans (O'Connell et al., 2011a; Boxberger et al., 2009).

The time constant for loading in human discs was estimated at 4 h (O'Connell et al., 2011a). However, the test duration in these experiments (4 h) was too short in comparison to the diurnal loading time. The overall loss of disc height was calculated by extrapolating the measured change in disc height in time. However, the validity of these extrapolations can be questioned.

In this study, we investigated the choice of model and the effect of testing time on the validity of predictions on creep behaviour of human discs. We hypothesised that the choice of model and test duration influences the prediction. To this end, we determined creep behaviour in human intervertebral discs with test durations beyond the typical duration of in vivo loading.

2. Material and methods

Ten intervertebral discs (IVDs; T9-T10; T10-T11 and T11-T12) were obtained from five human spines. The spines varied in age from 54 to 84 years. Spinal segments (i.e. the intervertebral disc and half of both the adjacent vertebral bodies) were cut from the spines with a band saw by two parallel cuts. All posterior elements were removed. Motion segments with osteophytes, vertebral fractures and/or disc narrowing were excluded from the experiment. The frozen discs were thawed immediately before testing. Tests were performed at room temperature. To prevent dehydration tests were performed in a saline bath. Since the overall testing time was 60 h an antibiotic (penicillin (200 mg/ml) and streptomycin (250 mg/ml)) was added.

The loading protocol was based upon in vivo intradiscal pressure measurements in humans by Wilke et al. (1999). The nucleus pressures in humans discs

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varies between 0.1 MPa for lying in prone position to more than 2.0 MPa during lifting activities. The test load represented lying in prone position during preloading and unloading phases (0.1 MPa) and standing upright during the loading phase (0.8 MPa). The duration of the test was based upon the time constants as reported in literature (O'Connell et al., 2011a). The complete test cycle consisted of three phases. IVDs were first preloaded for 12 h. The preload was then followed by a loading phase of 24 h and an unloading phase of 24 h. The duration of the loading phase was equal to six times the reported time constant.

Loads were applied by an Instron hydraulic testing devise (Instron 8872 Canton, Massachusetts). Prior to the test, the transverse area of each vertebra was measured. This area was used to calculate the appropriate compressive load. The load was applied to the superior vertebral body of the spinal segment and built up in 30 s. The compression load on and vertical displacement of the superior vertebral body was measured during testing with a sample rate of 10 samples per second.

Two different methods to calculate the parameters of the creep phase were used (i.e. deformation under a constant load). Both methods are commonly used in literature, a Kohlrausch Williams Watts function (KWW; Eq. (1)) and a Double-Voight model (DV; Eq. (2)).

$$x(t) = d_\infty (1 - e^{-(t/\tau)^\beta}) \tag{1}$$

$$x(t) = L\left[\frac{1}{S_1}(1 - e^{-(t/\tau 1)}) + \frac{1}{S_2}(1 - e^{-(t/\tau 2)}) + \frac{1}{S_E}\right] \tag{2}$$

The KWW function is a stretched exponential function. The three parameters of this model are: the change of disc height at equilibrium (d_∞) thus when the elapsed time equals infinity, the time constant (τ) and the stretch parameter (β). A stretched exponential function describes a decay function with two regimes. For a stretched exponential function with beta in the interval $0 < \beta \leq 1$, it describes an initial response described by a faster-than-exponential-decay regime followed by a slower-than-exponential decay regime (Berberan-Santos et al., 2005).

A Double-Voight (DV) model represents the mechanical behaviour of two damper/spring models connected in series. The four model parameters are: deformation of the fast Voight model at infinity L/S_1, the time constant of the fast Voight model τ_1, deformation of the slow Voight model at infinity L/S_2 and the time constant of the slow Voight model τ_2. Since creep is defined as deformation under a constant load, the parameters are calculated from the time point when the applied load is constant. Thus, the factor L/S_E, which describes the deformation prior to the creep phase, was not used.

Model parameters were separately calculated over the loading and the unloading test phase. The models were fitted to the measured data by a least squares method in Matlab (Mathworks Natick MA USA, version 7.1). To determine the effect of test duration, the KWW and DV parameters were calculated from a limited data set which consisted of the first 4, 8, 12, 16, 20 h of the test and finally from the full 24 h.

Since time constants defined in the two models cannot be compared directly, we calculated as model predictions the deformation at equilibrium and a common time constant (d_{63}) defined as the time it takes to reach 63% of the deformation at equilibrium.

Finally, repeated measures analyses of variance were performed with the duration of the experiment and the choice of model as independent variables and change-of-height at equilibrium and the time-constant as the dependent variables,

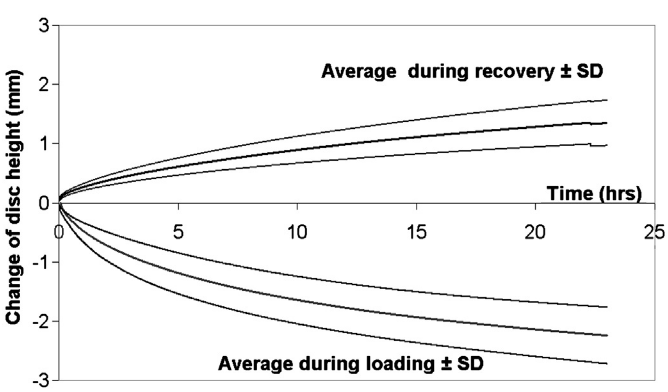

Fig. 1. The average changes of the disc height during a constant compression load (0.8 MPa) and subsequent unloading (0.1 MPa).

3. Results

The change of disc height did not reach a plateau in 24 h of loading or unloading. The length of the unloading phase was insufficient to compensate the loss of disc height during loading (Fig. 1). Moreover, recovery of disc height was still far removed from equilibrium, therefore deformation could not be modelled with sufficient certainty. Therefore, subsequent analyses were restricted to the loading phase.

Both models described the 24 h data of loss of disc height under constant loading well (Fig. 2a). The models provide a nearly as good fit to the data when the experiment is short. However, the predictions of both models beyond the test duration were substantially different. The extrapolation from 4 to 24 h (Fig. 2b) shows that the DV-model underestimates actual deformation, while the KWW model overestimates it. The average model parameters for Eqs. (1) and (2), based upon the 24 h data set, are presented in Table 1.

Model predictions as a function of test duration are presented in Figs. 3 and 4. As can be seen these predictions are dependent on test duration with effects levelling off at longer experiments. Consequently, the model predictions given with the KWW-model and DV-model vary with test durations (Tests of Within-Subjects Effects): Type of model: $F = 14.47$, $p < 0.004$ (Greenhouse-Geisser), Time: $F = 12.20$, $p < 0.002$ (Greenhouse-Geisser) and Type ∗ time: $F = 15.13$, $p < 0.001$ (Greenhouse-Geisser). Predictions differ clearly between models, but seem to converge to the same value with increasing test duration

Table 1
Average model parameters for the Stretched-Exponential model (Eq. (1)) and the Double-Voight model (Eq. (2)) estimated over 24 h of loading. Values in brackets are standard deviations.

	τ	d_∞	β	
KWW	17.34 (±9.29)	−3.15 (±0.70)	0.67 (±0.05)	
	τ_1	d_1	τ_2	d_2
DV	12.48 (±2.47)	−2.07 (±0.55)	0.82 (±0.32)	−0.50 (±0.35)

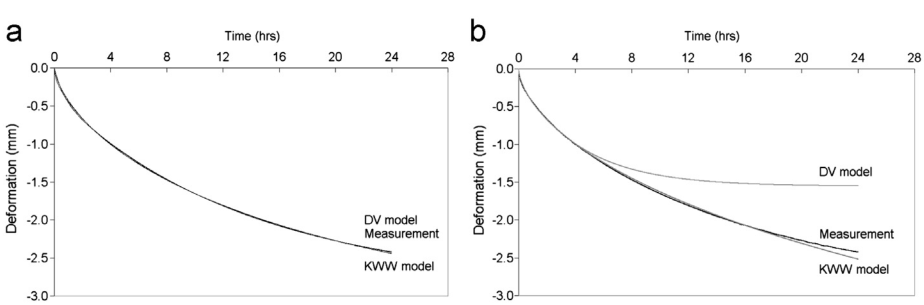

Fig. 2. Typical example of the change of disc height during constant loading. (a) Actual data of one specimen during 24 h of loading and the fit of both models to these data. R-squared of the fit: DV: $r^2 > 0.9999$; KWW: $r^2 > 0.9999$. (b) The same data with the model fit based on the first four hours of the test, extrapolated to 24 h. R-squared of the fit: DV: $r^2 > 0.9469$; 4 h KWW: $r^2 > 0.9985$.

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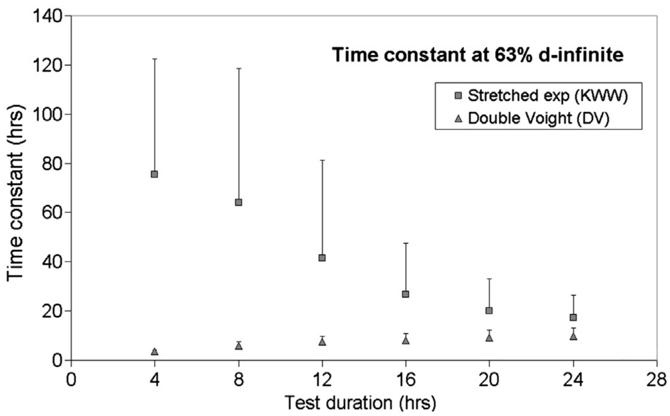

Fig. 3. The average estimated time point at 63% d_∞ (d_{63}) of the loading phase as a function of test duration.

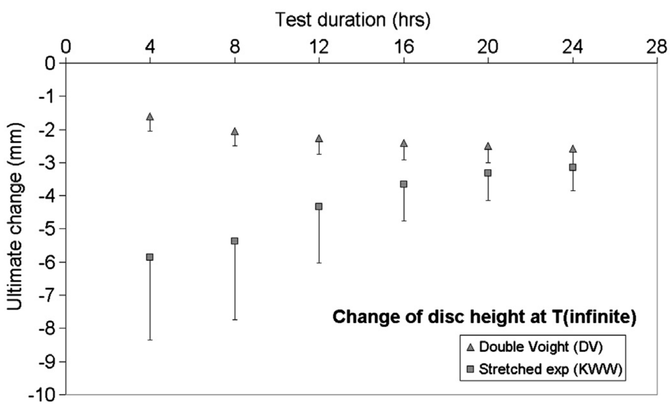

Fig. 4. The average estimated loss of disc height at equilibrium as a function of test duration.

4. Discussion

In this study, we investigated the effect of test duration and choice of model on the validity of the predicted creep behaviour of a human IVD. We measured the axial deformation of human IVDs under loading in a 24 h test and used this data to model creep behaviour. We showed that there was a pronounced effect of test duration on the validity of predicted creep deformation. As we measured creep behaviour for 24 h, we were able to improve model parameters with respect to previous values in literature. The estimated time constant of creep deformation was at least 12.5 h. This time constant implies that in-vivo a recurring, stable, daily pattern occurs without reaching equilibrium at the end of the 16 h of loading or the 8 h of unloading (Ludescher et al., 2008).

In the present study, thoracic discs were used, which are smaller than lumbar discs. It is to be expected that the time constant of lumbar discs will be larger, since the volume of the disc increases roughly with the 3rd power of the disc dimensions, while the area increases with the square of the dimensions. A rule of thumb for estimating a time constant is that the measurement time should be at least 5 times the time constant. The estimated time constant of 12.5 h implies that the 24 h test in the present experiment was too short. Hence, the problem is that the time constant of the human spine is so large that tests will take days. For a human thoracic intervertebral disc the required test duration would be in the order of 75 h for loading only. The outcome of shorter experiments, using any of the two models, will suffer from systematic errors. These errors will not be evident from a statistical analysis. To our knowledge all previous studies suffer this shortcoming. We suggest that two models, like the models used in the present study, can be employed to define an upper and lower limit to the time constant, since these two models approach the true value from opposite directions.

Variation in test duration had a larger impact on the KWW model than on the DV model (Figs. 3 and 4). However, both models converge to the true value with increasing test duration. Both models were applied to the creep phase only and not to the first part of the experiment in which the compression load was applied, allowing a direct comparison between both models. The KWW model only describes the creep phase, whereas the DV model in principle also models the immediate response.

The test environment was designed to mimic the in vivo environment of the intervertebral discs as much as possible. The specimens were tested in a saline bath at room temperature to slow down the natural decay and secondly antibiotics were added to the bath to control bacterial growth. Previous experiments in our lab showed that we could test caprine discs in this system for 72 h without a change in mechanical behaviour (van der Veen et al., 2009). This indicates that that decomposition of the disc presumably did not play a role in the outcome of this study. The samples had been frozen prior to the test and were thawed before the experiment. However, freezing and thawing of samples does not influence the biomechanical behaviour of the spine (Dhillon et al., 2001).

In conclusion, we showed that creep of the IVD in compression takes more than 12 h to reach 63% of equilibrium deformation. Although both KWW and DV models describe, experimental data well, typical test durations are too short to obtain valid model parameters. Extrapolation beyond the test duration, even if this exceeds the physiological loading time, yields overestimation of deformation by KWW models and underestimation by DV models.

Conflicts of interest statement

No funds were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

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